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I. INTRODUCTION

A generalized theoretical method for correcting wind tunnel test data on V/STOL models to the required flight condition of free air has been developed over the past two decades. An initial analysis of the ground effect on a lifting propeller was made at the Georgia Institute of Technology as early as 1940. This analysis led to an extensive and noteworthy series of publications by H. H. Heyson of the Langley Research Center in which the theory of rotor ground effect was refined and applied in its more advanced form to the first calculations of wind tunnel wall effects in helicopter testing. Extension of the theory to more general classes of V/STOL configurations was also accomplished by Heyson, supplemented by very complete tables of calculated correction factors.

In all these theoretical analyses, however, two major simplifications exist which are open to question. First, no attempts to account for possible slipstream or downwash curvature were made; and, second, there has been no consideration given to the momentum or energy exchange due to mixing of the slipstream with the tunnel main flow. In the extreme cases of pure hover and pure forward propulsion, these effects are of no importance. However, in the difficult transition regime between hover and forward flight, both simplifications may be unjustified. The first step toward inclusion of both mixing and curvature has been taken by Kirkpatrick in a Master's thesis at the

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University of Virginia. Although his calculated correction factors agree with the earlier values in the aforementioned extreme cases, they exhibit noticeable departure from Heyson's results in the transition-flight range of slipstream angles. Such discrepancies suggest that some additional theoretical work should be performed in which even more careful analysis of the importance of mixing and curvature are included and in which the possibilities of significant non-uniformities in approach flow as well as incipient separation from one or more boundaries are entertained by revised mathematical models. In addition, these theoretical models and their resultant predictions of the flow fields surrounding high-lift sources in finite wind tunnel test sections must be subjected to careful and conclusive experimental tests. It is the purpose of this research program to perform these dual analytical and empirical tasks.

II. PROGRESS REPORT

Progress to date on this research program will be discussed in two distinct phases: analytical and experimental. The analysis has proceeded very much in accordance with the work statement of the original proposal, while the experimental phase has been oriented toward completion of adequate wind tunnel facilities and has therefore not produced any test results or data.

A. Theoretical Analysis

In order to investigate theoretically those factors which influence the curvature of a jet directed at an arbitrary angle into a free stream, it was decided to review the work done originally by Kirkpatrick on this subject. The purpose of this investigation is to find an expression for the curvature which closely approximates the paths of jets as found by experiment.

Kirkpatrick assumed two factors which contribute to the bending of a jet: the mixing of the free stream with the slipstream, and the equivalent drag on the slipstream. It was decided that his expression for the mixing contribution represents the best presently available approximation to the real case, and therefore current theoretical efforts have been concentrated on finding a better mathematical model for the effects of drag on the jet slipstream.

In his development of the drag model, Kirkpatrick assumes:

1. No mixing-drag interaction, i. e. , the jet centerline velocity decays in the same manner as a jet exhausting into still air.
2. The cross-section of the jet perpendicular to the jet centerline is circular at every station along its length. It was felt that for a first approximate model of drag, the initial assumption is a good one. However, experimental investigations show that the slipstream does not remain circular.

In fact, after a very short distance down stream, the jet profile in a direction normal to its centerline assumes a kidney shape and retains its shape all the way downstream.

It was therefore decided to base the drag coefficient on this more realistic kidney shaped cross-section. This lowered the drag coefficient 8%, but allowed the area subject to drag to increase in accordance with experiments. In incorporating this assumption into the present model, it became necessary to alter Kirkpatrick's calculation method and equations. By relating initial vertical momentum to the vertical momentum downstream, Kirkpatrick removed the direct dependence of drag upon the width of the jet. Because of the odd shaped profile assumed, it was not possible to perform this separation in the present study. Therefore it was found necessary to derive an empirical expression for the width of the jet. This was done using the profiles found in Jordinson's report. The jet width was found as a function of two variables: distance along the jet centerline and ratio of initial jet velocity to free stream velocity. It should be pointed out that this expression is not thought to be the best possible, but it is the best available from the limited experimental information at hand.

Having derived a new and more realistic drag expression and employing Kirkpatrick's mixing model, the jet paths were then calculated by numerical methods for various velocity ratios. A program to perform these calculations was written for the University of Virginia's Burroughs B-5500 digital computer. The program was tested and several revisions were made to provide reasonable flexibility and accuracy.

A further numerical example was calculated in which it was assumed that drag had no effect at any location downstream from the core region of

the jet. This case was considered in order to provide some quantitative idea of the relative importance of drag in contributing to the slipstream curvature.

It was found that drag definitely has a significant effect on the curvature. The slipstream paths found for the revised Kirkpatrick model and for the model with drag operating only on the core region were found to differ by a large amount, the latter providing essentially negligible curvature.

These results are summarized in the attached figure, in which the three theoretical models are presented in comparison with two sets of empirical slipstream curvature data. The velocity ratio of 4.3 was chosen from those tests reported by Jordinson, and the empirical fit suggested by Margason from recent tests at Langley Research Center is presented for this ratio.

It is also felt that the particular numerical value of the drag coefficient is a significant factor in the theoretical model chosen for drag, since preliminary calculations indicate that a small change in drag coefficient results in a large change in curvature. Investigation of this effect is being carried on at present and will be continued over a range of coefficients and velocity ratios. In summary, Kirkpatrick's work has been critically examined, and a new model has been derived for drag, showing not only that the drag force is a major contributor to the curvature in all cases, but also that the theoretical model assumed for this drag is highly significant.

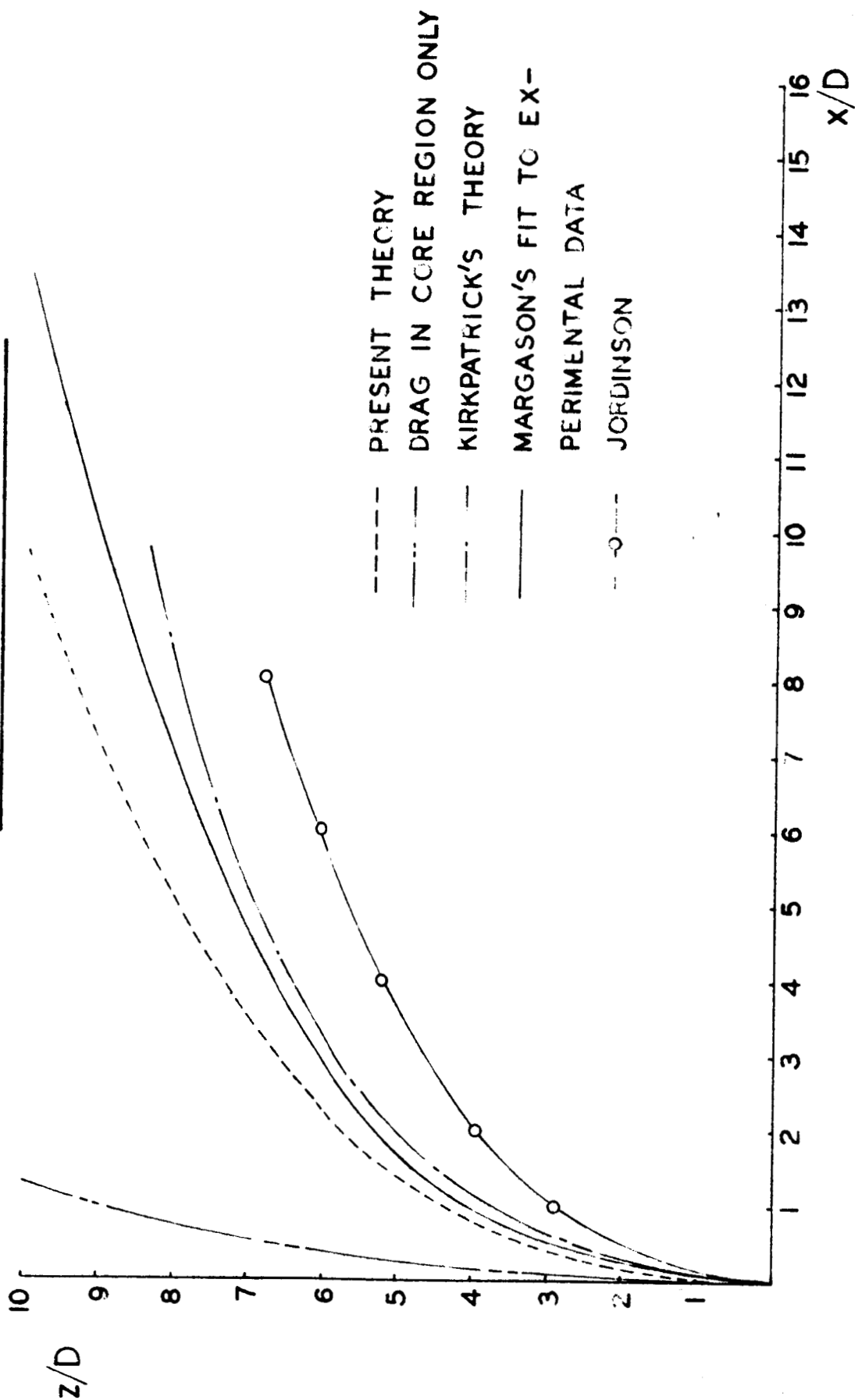
B. Experimental Program

Two subsonic wind tunnels, differing greatly in size but of similar speed range and test section design, are in final stages of construction and instrumentation for use on this research program. During the initial phase of this grant, work proceeded on both these facilities.

Longitudinal pressure traverses were obtained along the contraction section walls of the small tunnel (0.7 ft. - by 1.0 ft. test section) and compared with the two-dimensional, inviscid calculations which had provided the initial design for the contraction contour. This comparison is then intended to be applied to similar perfect fluid calculations for the large tunnel (5.0 ft. - by - 3.5 ft.) contraction section with the expectation of providing uniform rectilinear, vortex-free flow in the test section. Scaled-up models of the smaller, or pilot, tunnel contraction streamlines have been altered to fit the available space for the large tunnel; and two possible contours for these streamlines have been chosen for both the top and side walls of the contraction section. All four of these inviscid flow models have been examined by two-dimensional graphical analysis techniques to determine the combination of wall pressures which will provide the best match of top and side wall flows without encountering adverse gradients and accompanying boundary layer separation.

Two important additions to the pilot tunnel facility have been designed by undergraduate students as senior thesis projects, and it is anticipated that both these designs will be constructed and installed in the tunnel during the ensuing period of the program. The first of these is a variable-speed drive system which will allow precise tunnel air speed control over a range of velocities double that currently available. The second addition is a low-cost strain gauge balance system designed to measure three force and moment components over a sensitivity range of 400-to-one from maximum to minimum signal. Both of these facility improvements are essential in providing the experimental capabilities required for the proposed later phases of the research program.

JET PATHS FOR $V_{j_0}/V_F=4.3$



III. PERSONNEL

A. The principal investigator, Dr. George B. Matthews, Associate Professor of Aerospace Engineering, participated in this program approximately one-twelfth time during the first academic semester, through January 31, at no charge to the grant. Beginning February 1, this participation was increased to one-third time, with a charge to the grant of one-fourth time and a continuing contribution by the University of one-twelfth time.

B. Mr. William G. S. Hardy, a graduate student candidate for the Master of Aerospace Engineering degree, has been employed on this grant since its beginning at a one-half time level. Mr. Hardy has been responsible for performing all the numerical and theoretical analysis to date.

C. Messrs. John R. Stone and N. L. Thomas, undergraduate students who are candidates for the Bachelor of Aerospace Engineering degree in June 1966, have participated in the facilities design phase of the program since January 1966, at no charge to the sponsor.

D. Two technicians from the Department of Aerospace Engineering and Engineering Physics have contributed approximately one-fourth time to the construction of wind tunnel facilities at no charge to the grant.